

Electro-Optic Modulation: Systems and Applications

Demands for Wider-Band Beam Modulation Challenge System Designers

by Robert F. Enscoe and Richard J. Kocka

The laser, when coupled with a wideband modulation system, has many applications in data recording. As data recording has progressed, demands for wider recording bandwidths have marked the design of modulators. In this article, we'll consider the design and application of transverse-field electro-optic modulators using the Pockels effect. This effect produces a refractive index change when an electric field is applied to specific classes of crystals.

The electroded crystal may be considered to be a voltage-variable waveplate (Figure 1). When a voltage is applied, the polarization of the light exiting the crystal changes. This variation in polarization results in intensity modulation downstream from the output polarizer.

The ideal electro-optic material possesses all of the following properties:

- large change in refractive index per volt,
- high optical quality and transmission,

- low dielectric constant (low capacitance),
- low dielectric loss tangent (no dielectric heating due to a high-frequency electric field), and
- no distortions in modulator output from piezoelectric resonances.

Unfortunately, all crystals that exhibit the electro-optic effect are also piezoelectric. At low frequencies, one part of the total measured response results from a refractive index change produced by the applied electric field. Another portion is produced by piezoelectric strains. The

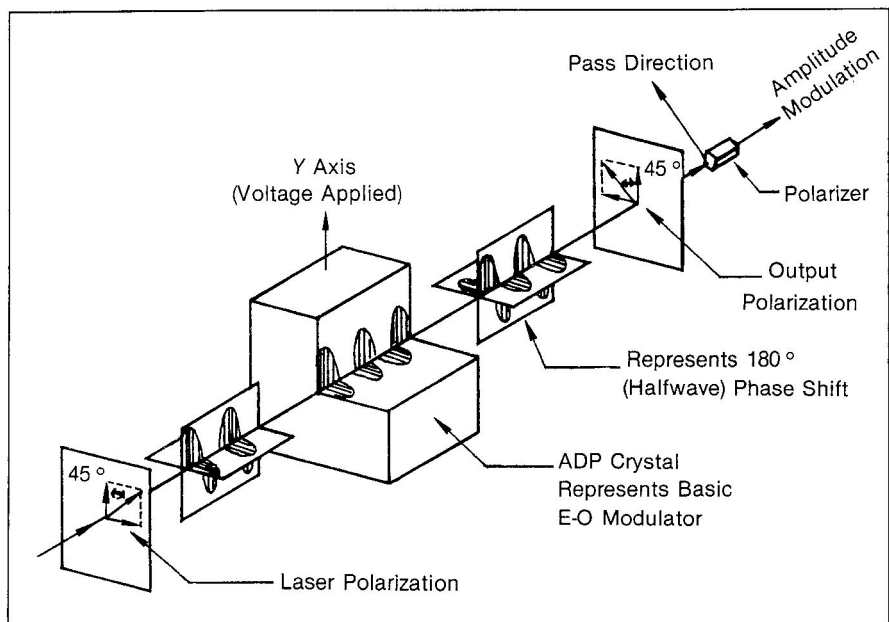


Figure 1. Retardation of laser polarization while a laserbeam passes through an ADP crystal. The output polarizer converts the phase shift into an amplitude modulation.

Robert Enscoe and Richard Kocka are vice-presidents of Conoptics Inc., Danbury CT.

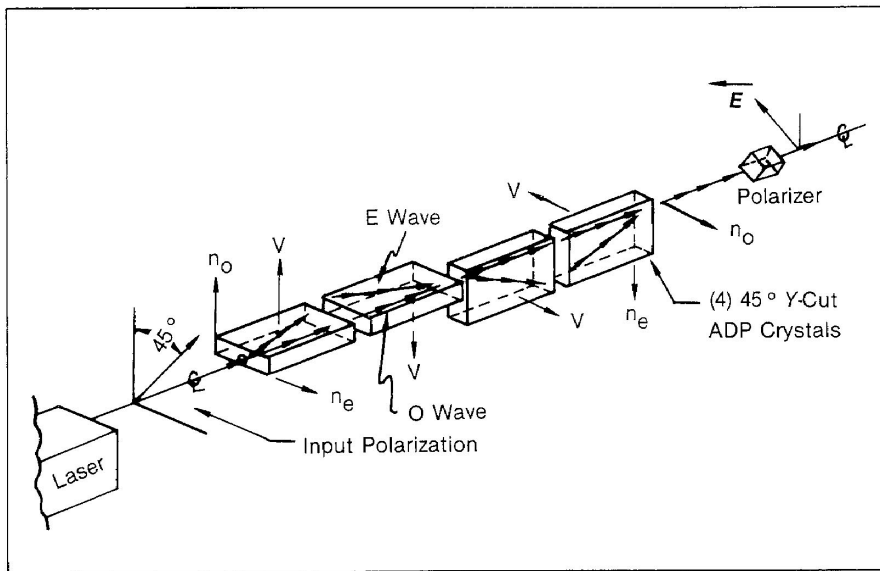


Figure 2. Typical transverse-field electro-optic modulator. The first two crystals cancel double refraction and the second pair cancel the natural birefringence.

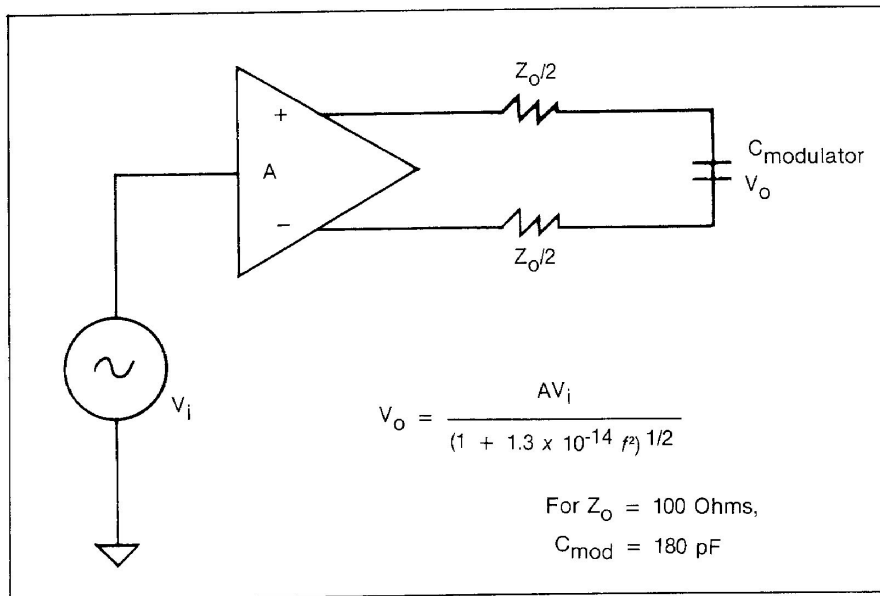


Figure 3. Equivalent circuit for low-frequency modulator (< 10 MHz). The crystal is modeled as a single, lumped 180-pF load.

piezoelectric strain contribution can be minimized by proper choice of material and orientation. Of all the electro-optic materials, the optimum choice in this respect is ADP ($\text{NH}_4\text{H}_2\text{PO}_4$) in the 45° Y-cut configuration. It yields a difference between low frequency and high frequency response of less than 0.4%. This compares very favorably with differences of 10 to 20% in other materials, which have severe amplitude and phase distortion near the mechanical resonance frequency. This crystal orientation (45° Y-cut) utilizes the R_{41} electro-optic coefficient, which, in addition to resonance-free response, has a low electro-optic coefficient sensitivity versus temperature.

Modulator Design

The aperture size and halfwave voltage (the voltage required to change the transmission from minimum to maximum) of the modulator are fixed by laserbeam dimensions and realizable levels of driver output. A 3-millimeter aperture will accommodate nearly all commercially available lasers without requiring beam-forming optics. Available power transistors will handle a 100-volt signal in a push-pull configuration. These two requirements generally determine the crystal dimensions.

The 45° Y-cut ADP crystal exhibits double refraction as well as birefringence. The first pair of crystals (Figure 2) are aligned to cancel out the double refraction. The second aligned pair is rotated 90° with respect to the first pair to cancel out the natural birefringence.

The operational stability of the modulator depends upon the four crystals being exactly aligned and of exactly the same dimensions. To insure that these requirements are satisfied, all the crystals used in the modulator are cut from the same crystal boule and are polished together to keep the lengths the same.

Drive Amplifier Considerations

Once the modulator's electrical characteristics have been defined, various design approaches may be evaluated for the optimum amplifier configuration. Let us assume the following typical modulator electrical drive requirements:

- laser operating wavelength is 514 nanometers,
- modulator capacitance is 180 picofarads, and
- halfwave voltage is 97 V at 514 nm.

Bandwidth considerations will now determine the configuration of both the driver and modulator. If system bandwidth is in the range of DC to 10 megahertz, the modulator may be driven as a lumped capacitor. A push-pull common-emitter stage with a balanced output impedance of 100 ohms will perform quite nicely throughout this range. Some shunt peaking in the amplifier output will deliver detected risetimes of 35 ns with less than 5% overshoot. Figure 3 depicts the modulator as a single 180-pF capacitor. Detected response is close to 10 MHz with short interconnecting cables between modulator and driver.

If bandwidth requirements exceed 10 MHz, the most efficient method of obtaining broader bandwidths is to configure the modulator as a balanced transmission line. In Figure 4 we have incorporated the individual crystals into a balanced line. The total capacitance remains unchanged, but, depending on how the crystals are electroded, the electrical cutoff frequency may be extended dramatically, yielding low voltage-standing-wave-ratios to the driving electronics. The bandwidth of this configuration follows a $(\sin x/x)$ response, with the first zero crossing at $1/\tau_d$, where $\tau_d = C_l Z_o$.

For a modulator with the same total capacitance and a driver with equal output impedance, the band-

width is improved by a factor of 2.5 over the simpler, lumped, single 180-pF case. This improvement comes at no increase in output power of the drive electronics. To extend the bandwidth past 25 MHz, the intrinsic propagation delay of the balanced line must be reduced. This may be accomplished either by reducing the total capacitance of the modulator (i.e., using a smaller optical aperture) or by lowering the characteristic impedance of the balanced line.

One 50-MHz system uses an optical modulator with a 50-ohm characteristic impedance, thus reducing the delay to 9 ns and doubling the useable bandwidth of the modulator. At this point, the drive electronics' power-handling capability must be doubled. Operating from DC through 50 MHz requires a much-broader-bandwidth output stage in the driver. A cascade-connected, grounded-base output stage is an excellent choice for broadband operation, because it removes any Miller capacitance at

Unfortunately, all crystals that exhibit the electro-optic effect are also piezoelectric.

its input, thus reducing the reactive component of the input impedance to the stage. The large-geometry output transistors required for high-current operation have intrinsically high output capacitance (C_{ob}) which cannot be tuned out as the stage response extends down to DC.

The common-base design increases the output break frequency of the amplifier, as the typical R_{bb} and associated external base impedance are negligible. Common-base operation is potentially the most unstable amplifier connection, since the device exhibits gain out to f_t . This makes small parasitic strays dominant at frequencies where the device still has forward gain. For this reason, the designer must pay careful attention to the electrical performance of the transmission line within the modulator.

Doubling the bandwidth again, to 100 MHz, presents a far more complex problem than going from 25 to 50 MHz. Extending useable response from DC to 100 MHz requires that the propagation delay of the modulator again be cut in half. To cut the impedance to 25 ohms would mean that the peak current in the output stage would be greater

than 3.6 amps. Devices with this current-handling capability have very large output capacitance and would, in effect, limit the response of the driver to less than the required system bandwidth. Paralleling smaller-geometry devices in the output would also parallel output capacitance, yielding the same results as the larger output transistor. Reducing the total modulator capacitance would cause a dramatic reduction in the useable optical aperture, thus precluding large-frame ion lasers without beam-forming optics.

One viable alternative is to section the modulator in two pieces, cutting the electrical delay of the modulator

in half, and then driving the modulator sections electrically in parallel, optically in series. Each modulator section would then rotate the plane of polarization 45°; when combined, they would deliver a full 90° rotation. This approach (Figure 5) would maintain a 50-ohm characteristic impedance for each section.

Maintaining a 50-ohm characteristic impedance keeps the interconnecting balanced cable at a commercially available value and also removes the difficult power-handling requirements that a 25-ohm structure would have required. The amplifier is capable of putting out more than 40 watts of RF power from DC to 100 MHz. All

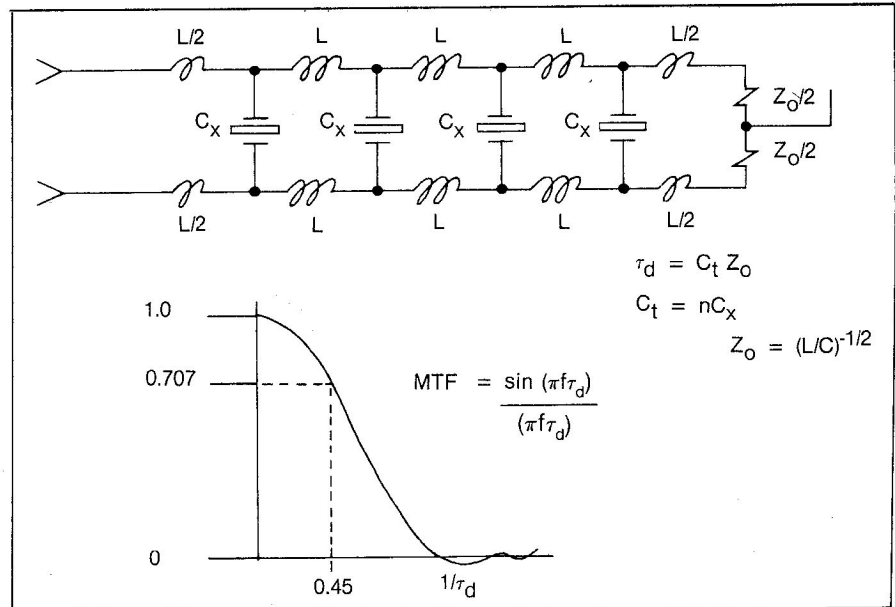


Figure 4. Equivalent circuit for high-frequency modulator (> 10 MHz), where the modulator is configured as a balanced transmission line.

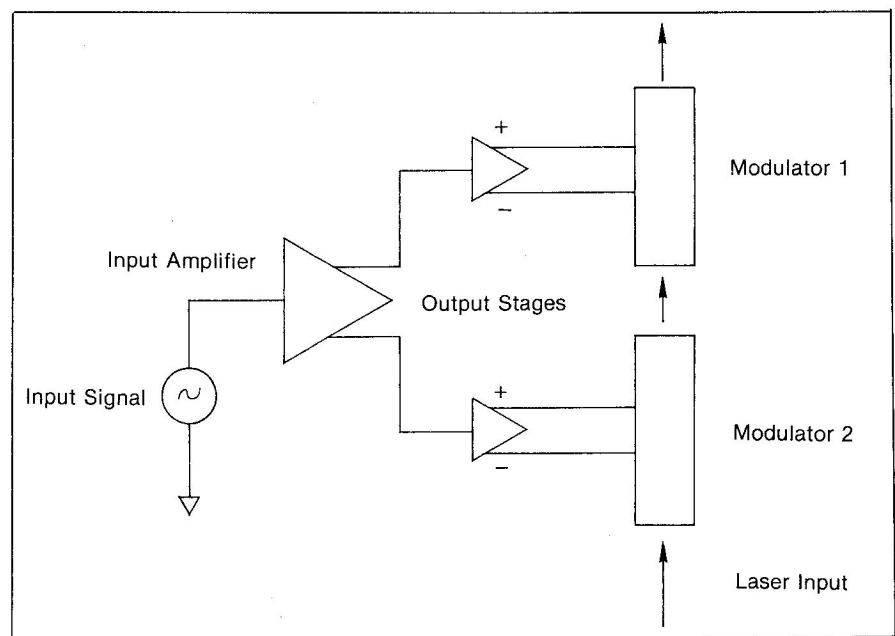


Figure 5. Sectioning a modulator into two pieces, with the electrical drive in parallel and the optical drive in series, is one means of extending bandwidth to 100 MHz without enduring difficult electrical-drive conditions.

of the transmitted RF, after propagating down the electro-optic modulator, is absorbed by high-power thick-film resistors, which terminate the line in the proper characteristic impedance. No electrical power is absorbed in the modulator head, as all the elements are reactive.

Large-signal, DC-coupled linear amplifiers have to deal with very large dynamic power changes within the active devices. This device dissipation change versus operating point shows up in the output as a signature or "thermal tail," which will affect the overall repeatability of the input/output transfer function. Good repeatability is essential in analog imaging recorders for tight correlation between the video input signal and resultant exposure level. Thermal time constants of small-geometry devices can be in the 2- to 3-microsecond range, well within the more dominant, low frequency imaging detail. The only practical way to minimize this effect is to make the quiescent amplifier current large with respect to the signal current, thus making the particular stage dissipation remain fairly constant. Closed-loop feedback is not practical because the inherent propagation delay through the amplifier is typically of the order of tens of nanoseconds, thus limiting the loop bandwidth to a few megahertz.

Modulator Bias Control

Since transverse-field modulators are path-length-dependent devices, the alignment of the laser to the crystal and temperature gradients affect the modulator's quiescent operating point. For this reason, a DC "biasing" voltage is applied to the modulator to properly position the quiescent operating point on the transfer function. This voltage is typically controlled manually by a high-resolution potentiometer or automatically by a high-gain feedback loop.

Typically, two different types of automatic servo systems can be used, depending on the application. For scanning systems, where a "dead time" (retrace) is available, a sampled loop is often used (Figure 6). During the dead time, a signal is applied to the system at J2 that instructs the loop to start operation. A signal is generated by the clock, amplified by the RF power amplifier, and sent to the modulator. A photodetector examines the resultant modulation, while a sample-and-hold extracts amplitude phase information. The resultant error

signal (if any) is amplified and applied to the modulator through the bias amplifier to reduce the operating point error. The sampled system can set the operating point at either minimum or maximum transmission, as required by system format.

In the second type of system, generally used in continuouswave systems such as videodisk mastering (Figure 7), the average optical power exiting the modulator in both the throughput and rejected ports is measured, compared differentially, and amplified. The differential error is then reduced by the high-gain negative-feedback loop. This format sets the modulator's operating point at the 50% transmission level.

Applications

Electro-optic modulators and modulation systems have been available for many years. They have found use in many applications requiring amplitude or phase modulation of cw or pulsed lasers. They offer speed and optical efficiency without the need for beam-forming optics. Some of the more common applications include the following:

Imaging and Data Recorders. High-speed recording of analog imagery or digital data on photographic film has both military and commercial applications. As the state of the art in laserbeam recorders advances, the need for broader modulation bandwidth and higher laser throughputs increases. Electro-optic modulators can deliver

this performance without compromising overall beam geometry.

Disk Recorders. Videodisk mastering has been entirely dominated by electro-optic systems. The "mother" disk is typically written with a 7-MHz FM-encoded format by a largeframe argon laser and a 50-MHz electro-optic modulation system. This combination delivers high power density and 7-ns rise-and-falltimes. The high frequency response of this system allows the resultant recorded pit geometry to be shaped correctly by band-limiting the input signal.

Digital Recording. The extremely large storage density capability, rapid access time, and archival storage properties of optical media make it attractive over traditional magnetic formats. Real-time single-track data recording of over 100 MHz is attainable with the laser-based system. Other applications include seismic recording for oil well exploration; color separation and halftone screen generation for reprographics; and recorders for the entertainment industry that convert either real-time television camera or videotape recorder output to 35- or 70-mm film. This allows electronic "special effects" and editing to be done before the picture is recorded.

Electro-optic modulators also lend themselves to many research and development applications such as polarization rotators in high-speed ellipsometry, broadband optical

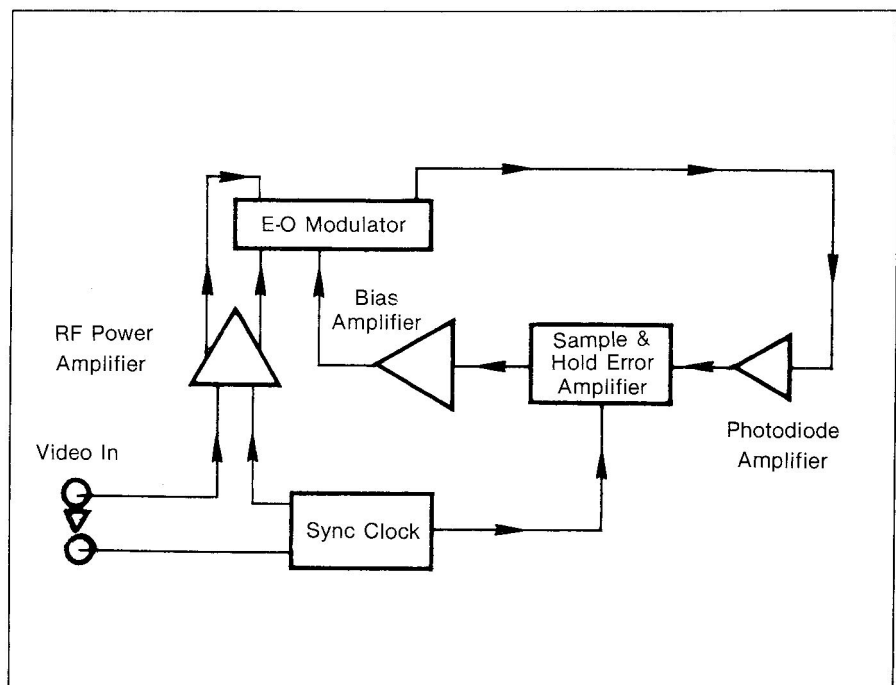


Figure 6. Servo control technique for a rastered scanning system takes advantage of the "dead time" in the flyback. The operating point can be either the 0%- or 100%-transmission level.

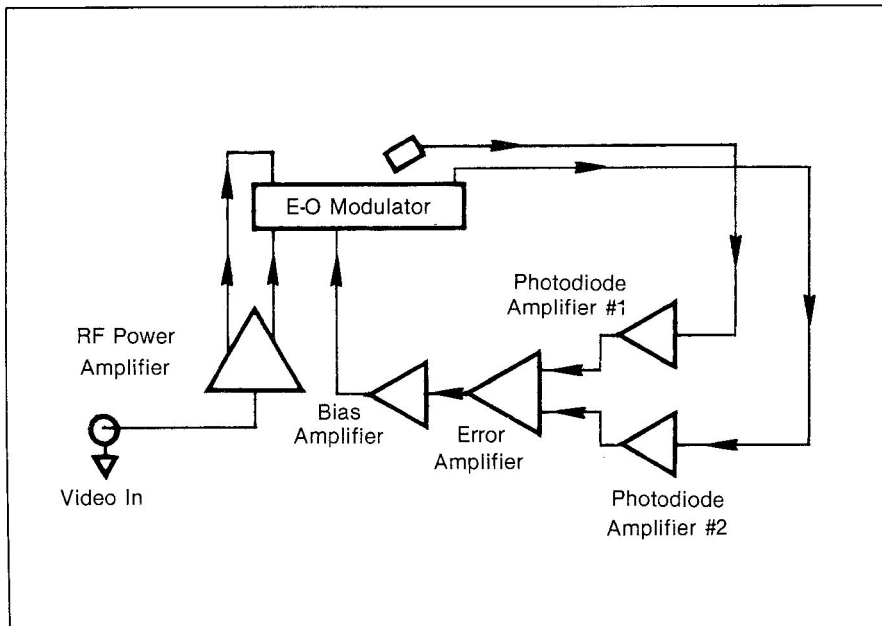


Figure 7. Servo control for a cw operating system provides continuous control of the output signal. The operating point is at the 50%-transmission level.

feedback loops for plasma noise reduction of argon and dye lasers used in Raman spectroscopy, and high-speed pulse selection of picosecond pulses from a modelocked train. Electro-optic modulation systems offer the system designer

very broad modulation bandwidth along with high optical efficiency. No dedicated beam-forming optics are required, and the interface requirements placed on the host system are minimal. □

Suggested Readings

1. Bruce H. Billings, "The Electro-Optic Effect in Uniaxial Crystals of the Type XH_2PO_4 ," *J. of Opt. Soc. Am.*, October 1949, April 1950, and January 1952.
2. M. Dore, "A Low Drive-Power Modulator Using a Readily Available Material ADP," *IEEE J. of Quant. Elec.* **QE-3** (11), November 1967.
3. Joseph F. Stephany, "Piezo-Optic Resonances in Crystals of the Dihydrogen Phosphate Type," *J. of Opt. Soc. Am.*, February 1965.
4. Edward Hartfield and Brian J. Thompson, "Optical Modulators," Section 17 of *Handbook of Optics*, edited by Walter G. Driscoll, McGraw-Hill, 1978.
5. A. Moritani, Y. Okuda, and J. Nakai, "Use of an ADP Four-Crystal Electrooptic Modulator in Ellipsometry," *Appl. Opt.*, May 1, 1983.
6. K. Compaan and P. Kramer, "The Philips VLP System," *Philips Tech. Rev.* **33**, 1973.
7. Yoshihiko Honjo, Ichiro Veno, Keiji Ozwa, Kanji Kayanuma (Victor Co. of Japan), Yoshihiro and Takafumi Sugano (Matsushita Electric Industries), "Mastering-Process for VHD/AHD Video Disc System."
8. K. Nakagawa and Y. Takenoya, "Laser-Beam Scanner by Multireflection," *Proceedings of the IEEE*, **70** (8), August 1982.

The most complete line of sophisticated electro-optic modulation systems.

Conoptics has developed four laser systems with bandwidths ranging from 10MHz to 100MHz. These systems will satisfy a wide range of applications, including: **Audio and video disc mastering, D.R.A.W. systems, and high resolution recorders.**

We also offer a Laser noise reduction system for applications in image reconstruction and Raman spectroscopy.

Modulators can be purchased separately by those who wish to use their own electronics.

*Please write or call for
our detailed data sheets.*

conoptics  **INC.**

19 Eagle Road, Danbury, CT 06810  Telephone: (203) 743-3349

FAX: (203) 790-6145 Telex: 643770